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Influence of soft magnetic material in a permanent magnet synchronous machine with a commercial induction machine stator

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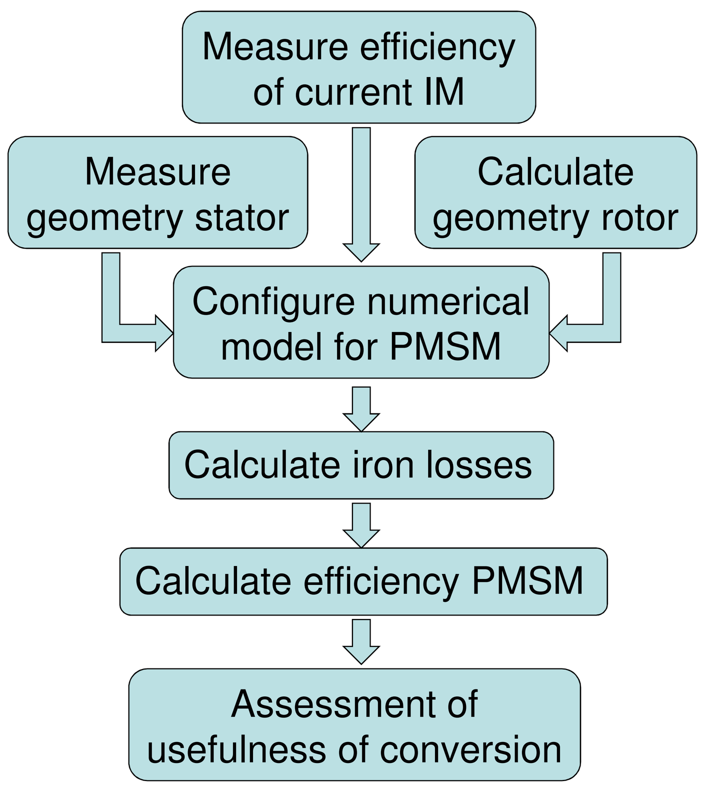
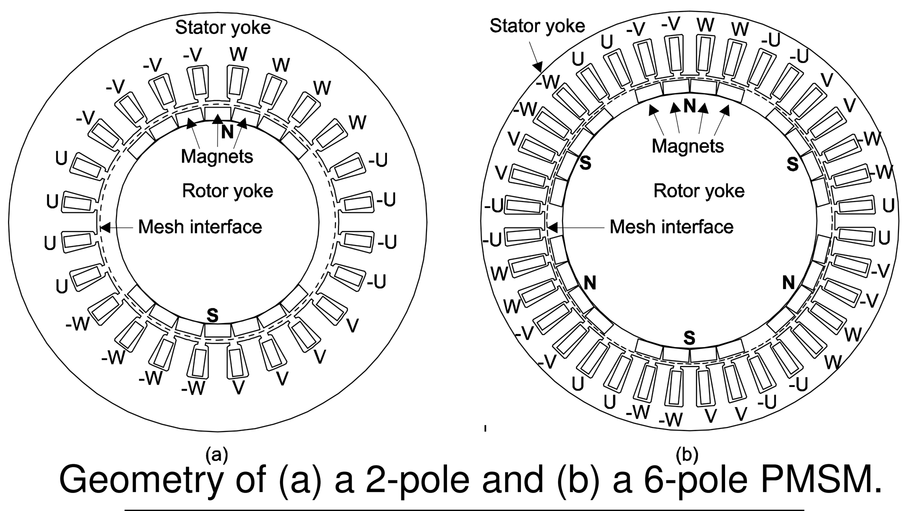
Introduction

- The efficiency of a commercial Induction Motor (IM), which is robust and cheap but where efficiency is low at low speed and power, can be optimized by:
  1. Converting the rotor to a synchronous rotor
  2. Replacing the electrical steel in the stator by another material grade
- To compare the several machines, we use the average and maximal efficiency that are defined in a torque range $0.5T_{nom} – T_{nom}$ and in a speed range $0.5\Omega_{nom} – \Omega_{nom}$.

Methodology





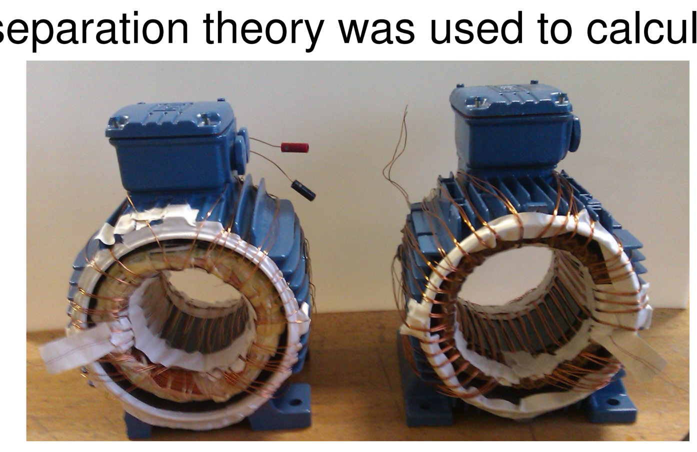
Geometry of (a) a 2-pole and (b) a 6-pole PMSM.

Numerical model PMSM's

Properties	*2-pole PMSM (a)*	*6-pole PMSM (b)*
Nominal speed	3000 rpm	1000 rpm
Nominal power	3.0 kW	1.5 kW
Outer diameter	160 mm	158 mm
# stator slots	24	36

Numerical and loss model

- Two PMSM's were simulated by using a transient 2D Finite Element Model (FEM), taking into account the rotor movement.
- A time domain loss model based on the loss separation theory was used to calculate the iron losses.
  - The loss model parameters were estimated based on loss measurements of the stator.
  - Hysteresis loops could be measured of the material inside the machine in order to identifiy the parameters in the static and dynamic hysteresis model.



Stator with excitation and measurement winding.

- The loss parameters were determined by a function based on five material specific coefficients [*a*,*α*,*b*,*c*,*d*] that gives the loss in W/kg over a time period of the magnetic induction.
- The total average power $P(B_p,f)$: $P(B_p,f)=P_{hy}(B_p,f)+P_{dy}(B_p,f)$
- Coefficients *a* and *α* are fitted based on hysteresis loop measurements with peak inductions B_p between 0.05T and 1.8T and 0.5Hz frequency: $P_{hy}(B_p,f)=aB_p^{\alpha}f$
- The equation in time domain loss model:

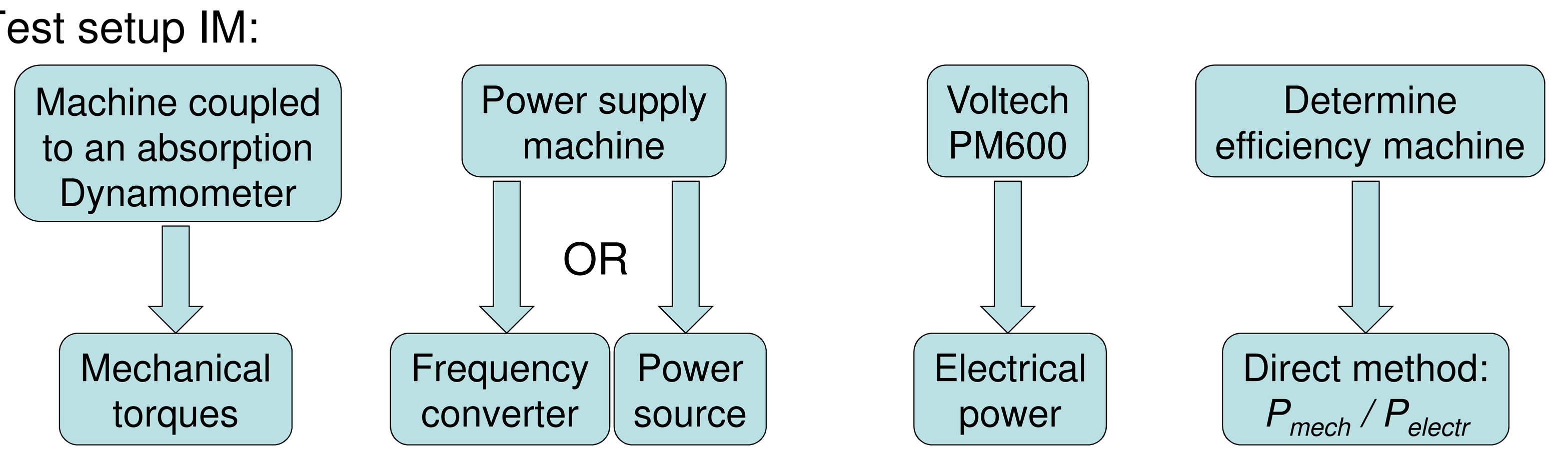
$$P(B(t))=b\left|\frac{dB(t)}{dt}\right|^2+c\left|\frac{dB(t)}{dt}\right|\left(\sqrt{1+d\left|\frac{dB(t)}{dt}\right|}-1\right)+P_{hy}(B(t))$$

b, *c* and *d* are fitting parameters. If the electrical conductivity *σ* is known, *b* can be found as $b=\frac{\sigma D^2}{12}$ with *D* the sheet thickness.

- The losses in the copper stator windings are computed from the enforced stator current and the measured resistance at the steady state temperature of 50℃.

Experiments

- Two test setup's were made, one for the IM and one for the PMSM, both with the same stator.
- Test setup IM:

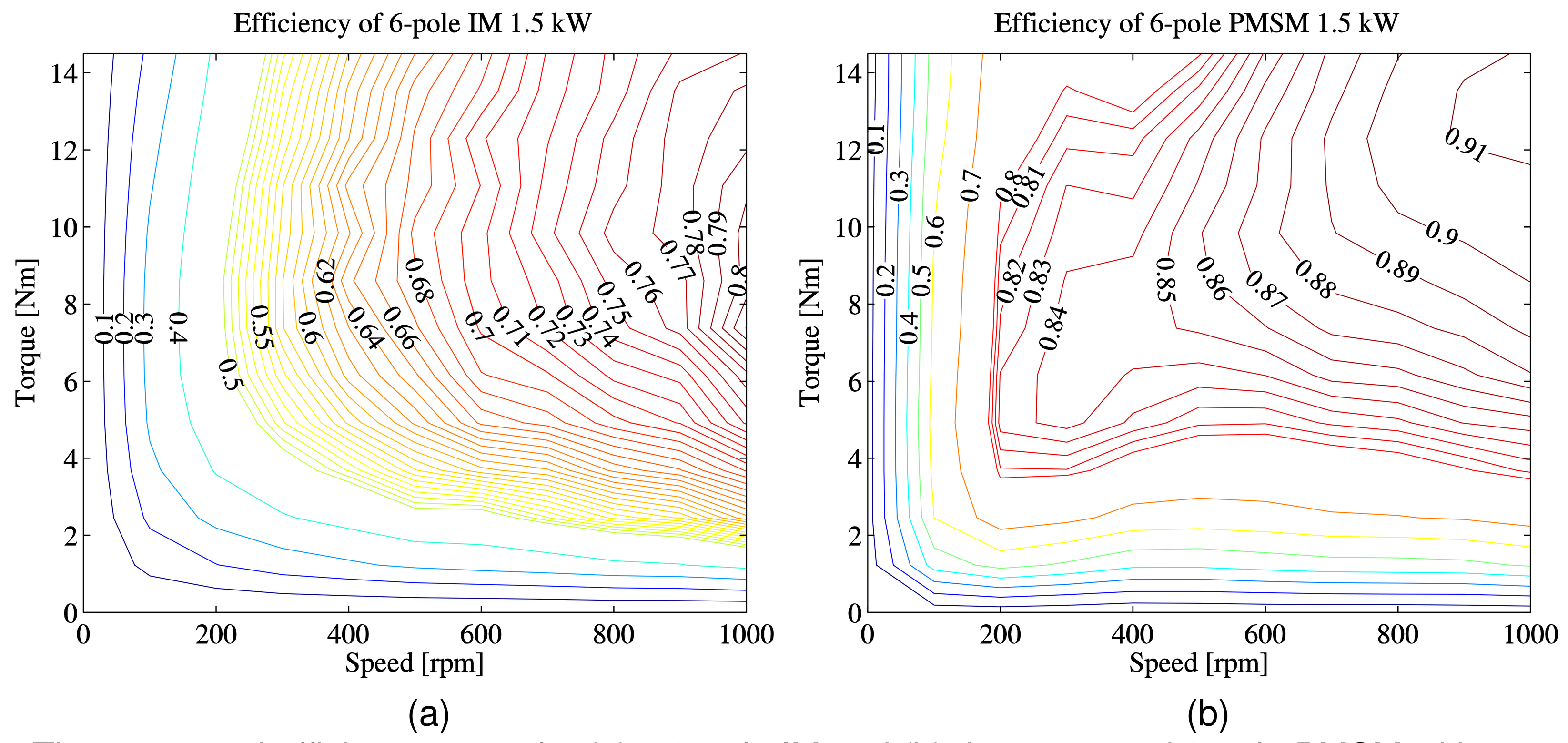


- Test setup PMSM:
  - Rotor reduced in diameter on a lathe and magnets were glued on the surface
  - Permanent NdFeB magnet rotor with unchanged stator.

The rotor of a 2-pole machine during construction.

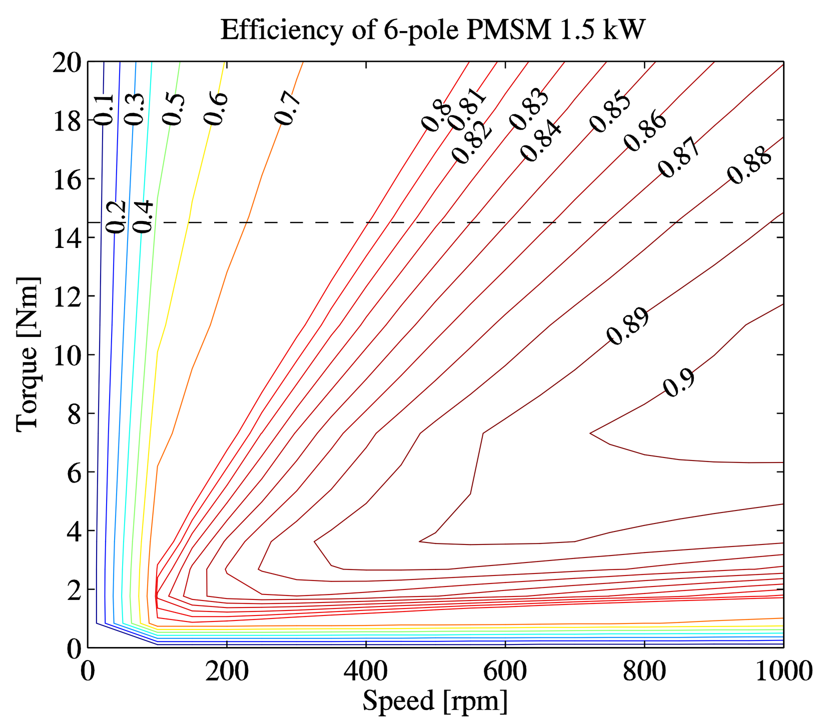
Results

- Measured efficiency maps of a 6-pole IM and the converted 6-pole PMSM:



The measured efficiency maps for (a) a 6-pole IM and (b) the converted 6-pole PMSM with original stator iron (M800-50A). Note for clarity of the figure, the contour lines are not equidistant for $\eta < 0.8$.

- For validation of the numerical model we also computed the PMSM's:



The computed efficiency map for a 6-pole PMSM with original stator iron (M800-50A). The dashed line shows the nominal torque, wich is the maximum in the measured efficiency map. Note for clarity of the figure, the contour lines are not equidistant for $\eta < 0.8$.

- The same was done for another machine, a 2-pole machine.
- The efficiency results for a 6-pole and 2-pole machine with original stator steel:

Efficiency of 1.5 kW 6-pole machine (M800-50A)

		Average efficiency	*Maximum efficiency*
Measured	*IM*	73.53 %	82.04 %
	PMSM	88.36 %	92.18 %
Computed	*PMSM*	88.29 %	90.70 %

Efficiency of 3.0 kW 2-pole machine (M800-50A)

		Average efficiency	*Maximum efficiency*
Measured	*IM*	83.24 %	86.27 %
	PMSM	85.47 %	89.72 %
Computed	*PMSM*	92.08 %	93.70 %

- In a second study the FEM of the 6-pole and 2-pole PMSM are simulated for different kinds of magnetic materials in the stator. The influence on the efficiency of magnetic materials such as M235-35A, M250-50A, M330-50A, M330p-50A and M600-50A was investigated. The loss parameters for each material were added to the loss model.

Efficiency of 1.5 kW 6-pole computed PMSM

Iron stator Soft magnetic material	*Average efficiency*	*Maximum efficiency*
M235-35A	90.15 %	94.10 %
M250-50A	90.16 %	94.04 %
M330-50A	90.00 %	93.86 %
M330p-50A	89.82 %	93.43 %
M600-50A	89.31 %	92.65 %
M800-50A (original)	88.29 %	90.70 %

Efficiency of 3.0 kW 2-pole computed PMSM

Iron stator Soft magnetic material	*Average efficiency*	*Maximum efficiency*
M235-35A	93.65 %	96.54 %
M250-50A	93.64 %	96.47 %
M330-50A	93.51 %	96.29 %
M330p-50A	93.31 %	95.90 %
M600-50A	92.92 %	95.30 %
M800-50A (original)	92.08 %	93.70 %

- The M235-35A magnetic material had the highest peak efficiency for both PMSM's.

Conclusions

- Small IM's with many poles, in this case 6-poles, are not efficient unless the IM is converted into a PMSM where the efficiency increases a lot.
- The electrical steel for the lamination stack plays an important role in efficiency improvement, but the gain of efficiency is lower than for the conversion IM to PMSM.